Application Note #4

Measuring Transmitter Power with the Oscilloscope

HF Amplifier Power Measurements:

Power is often defined as peak power, carrier power, average power, Peak Envelope Power (PEP) and sometimes incorrectly as RMS power. In the United States the Federal Communications Commission uses PEP to set maximum power limits for amateur radio transmitters. The maximum power allowed on certain frequencies using SSB modulation is 1,500 Watts PEP. PEP is the average power supplied by the transmitter/linear RF amplifier to the transmission line and eventually the antenna, during one radio frequency cycle at the crest of the modulation envelope, under normal operating conditions.

What is Electric Power

Electric power is the rate at which electric energy is transferred by an electric circuit. The unit of power is the Watt. Joule heating, is ohmic heating and resistive heating, it is the process by which the passage of an electric current through a conductor releases heat. It was initially studied by James Prescott Joule in 1841.There is potential power (no heating), instantaneous power and average power. When one volt is applied across a one ohm resistor, one ampere of current flows though the resistor. Since P=IE then the resistor is dissipating one Watt.

When power is defined over time it is expressed in Joules. One Joule equals one Watt per second; that is synonymous to one Watt second. When power is referred to as “instantaneous power”, it is expressed as a fraction of a Joule; for example if the instant of that power lasts for one Millisecond, that equals one Millijoule or one Milliwatt second.

It should be noted that the power applied to an ideal antenna does not heat the antenna. The antenna radiates the power (less any losses, which indeed heat the antenna). This radiated power is eventually absorbed by the atmosphere, natural and manmade objects, and also at the radio receiver's antenna and receiving circuits; eventually the energy is transformed either to useful work, or heat.

PEP may be more difficult to measure than CW power. Nonetheless, PEP is the average power during one radio frequency cycle at the crest of the modulation envelope and continuous wave (CW) power is also an average power, thus they are equal.

All power measurements rely on these formulas:

For DC power measurements, use:

$$P = E^2/R$$

For AC, PEP measurements, use:

$$P = (E_{avg})^2/R$$

Peak Power

Measuring peak voltage with an oscilloscope is not difficult, and generally, the load impedance (R) in amateur radio transmitters and transmission lines equals 50 ohms (sometimes 300 ohms). Making a peak power measurement is straightforward by measuring the peak voltage. Some users find it simpler to measure the peak-peak voltage. In that case, divide the results by 2 to get peak voltage.

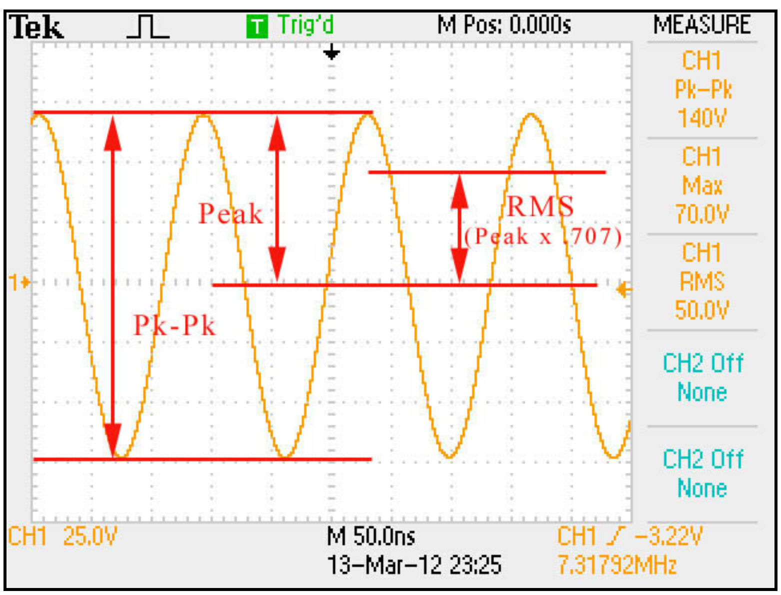

Figure 1, Oscilloscope display

See figure 1. Note, the Max (peak) voltage is 70 volts, which is half of the Pk-Pk voltage. To solve for peak power, square the peak voltage (*E*) and divide by 50 (the load impedance) So:

$$(70)^2 = 4900/50 = 98 \text{ watts Peak Power}$$

Average Power

Let's dispel the myth of RMS power. There is no such thing as RMS power. RMS is an abbreviation of Root Mean Squared. The term "Mean" is just another word for average. With respect to power calculations, the AC RMS voltage is the equivalent to the DC voltage. For example, 25V RMS or 25V DC across a non-inductive 50ohm load results in identical power dissipation of 12.5 watts in either case.

The RMS value by itself is not the comparable heating power and it doesn't correspond to any useful physical quantity; no heat, no power. Recall P=IE, and I=E/R. Voltage (E), nor current (I) by themselves generate power. The power is only produced when a current is induced by a voltage across a load R. Finally, RMS and average values of nearly all waveforms are different. One exception is a steady DC waveform, for which the average, RMS, and peak values are identical.

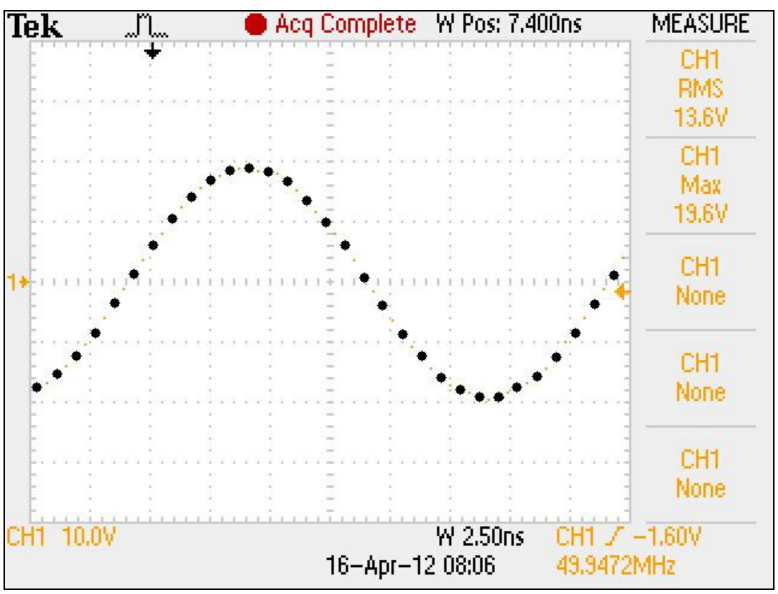

Figure 2 sampled sine wave

See figure 2. If one were to sample a waveform at regularly spaced times, and then add up their values and divide that total by the number of samples taken, one would have approximately the average value of whatever the waveform represents; this could be voltage, current or power. The less the time intervals between samples, the more accurate the average will be. The mathematical integration is a method to find what the value would be if we could minimize the time interval really close to zero. That's important if we want to calculate the exact average value of some waveforms. The corresponding formula for a continuous function (or waveform) $f(t)$ defined over the interval

$$T_1 \le t \le T_2$$

$$f_{\mathrm{rms}} = \sqrt{\frac{1}{T_2 - T_1} \int_{T_1}^{T_2} [f(t)]^2 \, dt},$$

Thus substitution volts for f we arrive at the familiar equation:

$$V_{\mathrm{rms}} = \sqrt{\frac{1}{T_2 - T_1} \int_{T_1}^{T_2} [f(t)]^2 \, dt}$$

Fortunately this mathematical integration can be reduced to the RMS values. And for an ideal sine wave that happens to be the peak waveform value multiplied by .707. So power is still power, whether PEP or average. The correct way to express average AC power is P_{avg}. as a result:

$$P_{avg} = (E_{RMS})^2 / R$$

We know that oscilloscopes are great tools to measure voltages of AC waveforms. For a perfect sine wave, multiplying peak voltage times .707 will give us RMS voltage. Some of the newer scopes make this step easy and calculate the RMS voltage directly. These calculations are quite accurate even for non-sinusoidal waveforms. See Figure 1, what is the average power if the peak voltage is 70 volts?

Step one: Calculate the RMS voltage (70 x .707 = 49.5 volts). You'll note that in Figure 1, the calculated RMS voltage is 50 volts not 49.5 volts. That is because the oscilloscope measurement was done on a somewhat imperfect sine wave, thus giving a slightly higher reading.

Step two: Square the voltage, and divide by 50 (the load impedance):

$$(49.5)^2 = 2450/50 = 49 \text{ watts Avg.}$$

A common error some make calculating average power is they multiply PEP by .707, i.e. 98 watts times .707. This results in an incorrect answer of 69.3 watts. Power is always calculated by squaring the voltage and dividing the result by the load impedance.

PEP Power

The International Telecommunication Union (ITU) Radio Regulations define the terms Peak Envelope Power (PEP) as:

"PEP means the average power supplied to the antenna transmission line by a transmitter during one radio frequency cycle at the crest of the modulation envelope taken under normal operating conditions."

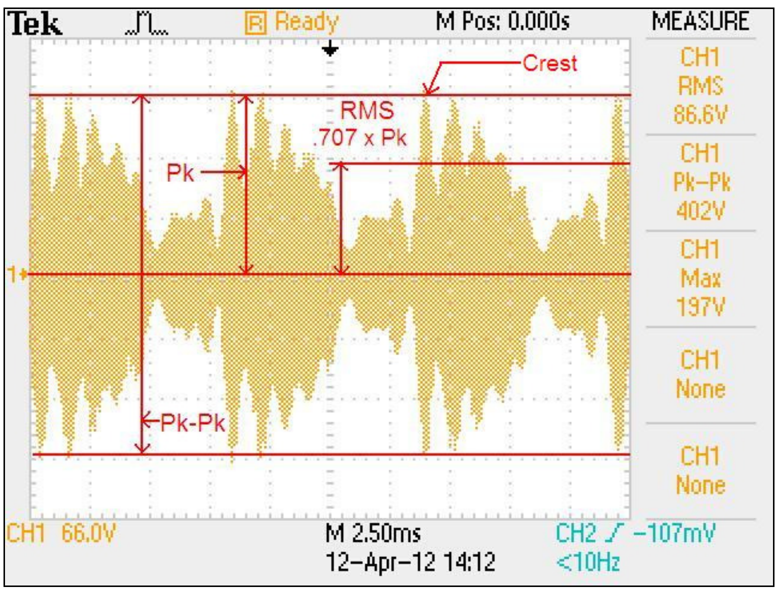

Figure 3 SSB Modulation

Understanding the definition of PEP, the question then arises what is meant by "*radio frequency cycle at the crest of the modulation envelope*"?

See figure 3. The crest of the modulation envelope is the peak value; this oscilloscope labels it as "Max". It is 197 volts. Note, that the scope calculated the RMS voltage as 86.6 volts which would be correct for a steady RF carrier. However, here the modulation is not a steady carrier, but instead represents the minimum and maximum modulation levels as an envelope.

The modulation envelope duration is 25mS over the entire display duration. At 7.3 MHz, this duration contains 182,500 individual radio frequency cycles. Since the scope calculates RMS voltage over all these cycles, we cannot rely on that calculation. So how do we obtain the RMS voltage for one radio frequency cycle? We know by examining the scope display that there must be at least one radio frequency cycle at the crest of the modulation envelope. The peak value of that cycle 197 volts. We also know that RMS voltage equals .707 times the peak voltage; so 197 x .707=139.3 volts. To calculate PEP power we again use this formula:

$$P_{avg}=(E_{RMS})^2/R$$

PEP means the average power. So we can substitute PEP for Pavg. Thus:

$$PEP=(E_{RMS})^2/R$$

Accordingly, applying this formula yields:

$$PEP = (139.3)^2=19,404/50=388\ watts.$$

Amplitude Modulation (AM) Power

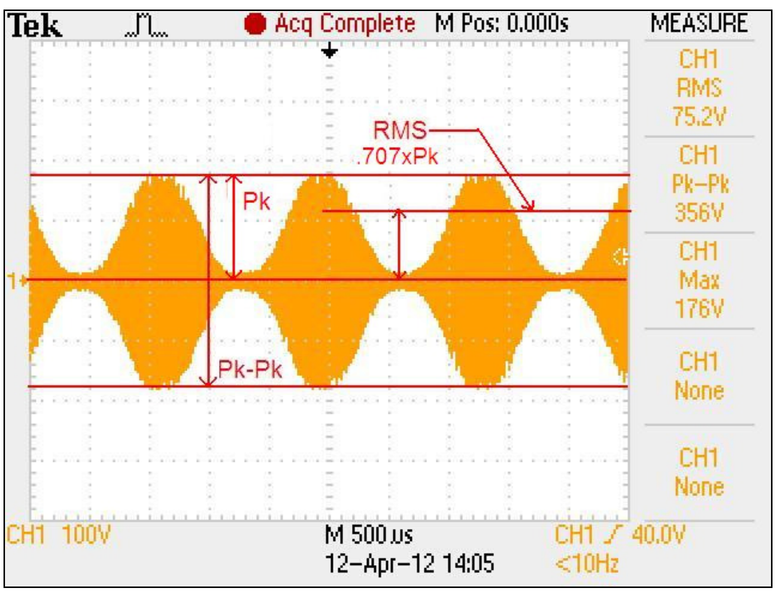

Figure 4 Approximately 90% AM modulation

See Figure 4, the PEP output of an AM transmitter at full modulation is four times its carrier PEP; in other words, a 100-watt amateur transceiver is usually rated for no more than 25 watts carrier output when operating in AM mode.

RF Power Meters

Absent a PEP function, virtually all analog power meters measure average power. Many low cost power meters are notoriously inaccurate as they are generally not calibrated to a known power standard. The Bird model 43®, and Heathkit® HM-102 are an exception. Their accuracy is guaranteed to better than 5% of full scale. The HM-102 employs an internal accurate calibration standard to which the meter is calibrated. The Bird® 43 slugs are individually calibrated at the factory against an accurate RF power source.

As a result, these two analog power meters are generally much more accurate than 5%. The accuracy of any meter can be verified to better 2% (the scope vertical amplifier specification) when an oscilloscope is used to measure the power and comparing that result to an unknown power meter.

PEP RF Power Meters

You may notice that your oscilloscope PEP measurements are consistently higher than that obtained by most RF watt meters. There is nothing wrong. That is because the oscilloscope, with its very fast rise time, can measure PEP based on peak voltages.

Most commercially available watt meters display average power only. Some RF meters employ a “PEP” function. They do this with a sample and hold circuit. This circuit needs to have a fast rise time, i.e. considerably faster than the PEP envelope components. Even then, some of these meters may not accurately measure the true PEP power. As a result, their PEP reading can be significantly lower.

One of the most reliable ways to confirm the accuracy of any analog or digital power meter is by using an oscilloscope with a calibrated vertical amplifier and sufficient bandwidth (normally twice the measured frequency).

Direct sampling power measurements with the Oscilloscope

Most modern oscilloscopes have a maximum calibrated vertical amplifier deflection factor of about 5 volts/division. With an accurate X10 voltage probe, the vertical amplifier can display up to 50 volts/division. Given the 8 vertical divisions normally found on an oscilloscope display, the maximum voltage measurement with a 10x probe is 400 volts peak to peak. That is the equivalent of 141.4 volts RMS, which in turn calculates to 400 watts into 50 ohms. Any measurement of greater power requires an RF sampler (discussed below).

The method used to make the power measurements is called direct sampling. Set the scope to the appropriate volts/division setting, sample the voltage applied to the center conductor of transmission line with an accurate 10x probe which in turn is connected to the scope's vertical input. This can be done with a "T" connection. For HF frequencies, the measured voltage will be quite accurate. The closer the sampling point is to the transmitter the better.

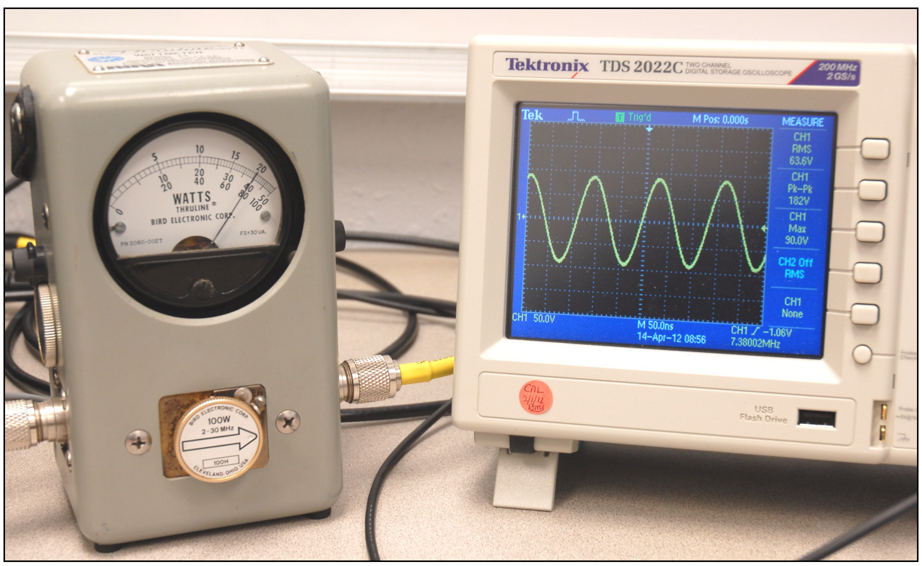

Figure 5 direct power measurement

The primary errors will be the result of the combined uncertainty of the specifications of the vertical amplifier and the 10x probe. However, these can be checked with an accurate signal generator such as a Tektronix® SG 503 constant amplitude calibration generator. My experience has been that the accuracy achieved is better than 2% and correlates with a Bird 43 ® power meter. In figure 5 the scope measured 63.6 volts RMS which equals 80.89 watts, and the Bird 43® indicates 80 watts. That's within +/- 1% well within the specifications of either instrument.

Problems with Direct Voltage Measurements

While it is possible to make direct high power measurements with an oscilloscope, such as 1500 watts, it is rarely done. For example, at 1500 watts, the RMS voltage is 274 volts, 388 volts peak, and 775.1 volts peak to peak. These levels can result in damaged equipment and potential injury or death to the operator. It is possible to use high power attenuators to reduce the voltage levels to a practical level. However, these attenuators must be able to take the full brunt of the maximum power to be measured.

The RF Sampler or Coupler (sampler)

Fortunately using an oscilloscope with an appropriate sampler is uncomplicated and provides accurate results of better than 1 db. One way is to measure the power is to load the amplifier directly into an antenna capable of radiating the maximum applied power. The preferred and most practical way, is to load the amplifier in a "dummy load", which is usually 50ohms. These dummy loads are inexpensive and simple to connect. But how do you measure the high voltage input to the dummy load? The best way to do this is with an RF sampler. The sampler reduces the power to a manageable level. The most common power reduction is a 1000 to 1. This equals -30 dB of the RF being sampled.

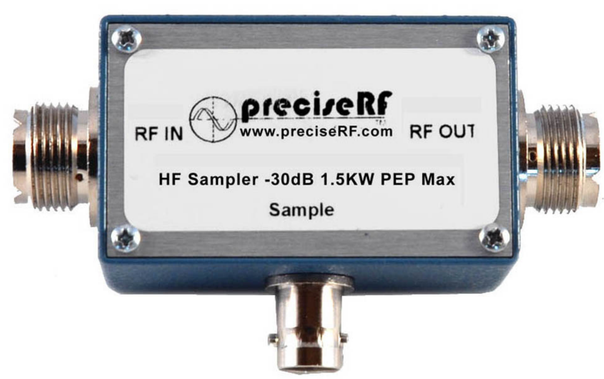

Figure 6 The HFS-1.5 HF sampler/coupler covers 2MHz to 50MHz. Employing a wideband transformer; it samples the high power RF (up to 1.5 KW PEP) from 2MHz to 50MHz.

Figure 6, The HFS-1.5 HF sampler allows for a maximum input of 1.5 KW, at HF frequencies from 2MHz to 50MHz with a sample transfer coefficient of - 30dB or a 1000:1 reduction in power. Most samplers, including this example, provide a "Sample" port which requires a 50ohm termination. Nearly all scopes have 1 Meg ohm vertical input impedance and do not have the necessary 50ohm input impedance. As a result, they require a 50ohm pass-through terminator at the scope's vertical input. However, when connecting the sampler to a spectrum analyzer, a pass-through terminator is not required since most spectrum analyzers have a 50ohm input impedance.

Using the Sampler to Measure Power

An ideal sampler with a -30 dB power reduction (1000:1) has a voltage gain/loss of 31.62. Therefore, to find the equivalent voltage (peak, pk-pk, or RMS) for -30dB, multiply the sampled voltage times 31.62. Using peak voltage allows for calculating power at any instant in time. If the peak voltage at the sampler port equals 2.83 volts, than the actual RMS voltage is 2.00 volts (2.83 x .707). Multiplying the RMS voltage by the gain/loss ratio 2.00×31.62 which we get 63.3 volts RMS. Calculate power using:

$P = E^2/R$ equals 80.05 watts

When comparing that measurement using a calibrated -30 dB sampler to the direct measurement in figure 5, (80.05 watts) correlates well with the previous direct measurement of 80.89 watts, and the Bird 43® indication of 80 watts.

Here is a sampler with a -20 dB power reduction (100:1) it has a voltage gain/loss of 11. To find the equivalent voltage (peak, pk-pk, or RMS) for -20 dB, multiply the sampled voltage times 11. For instance, if the peak voltage at the sampler equals 5 volts, that equals 3.54 volts RMS. The voltage at the sampler input is 3.54×11 which equals 38.9 volts RMS. Calculate power using:

$P = E^2/R$ equals 30 watts

A much quicker way to obtain PEP and average power measurement is to refer to Table 2 below. Connect the output of sampler port to the oscilloscope input (use a 50 ohm terminator at the scope input) and note the peak voltage. Move to the right and read the peak and average power in watts, or power expressed in dBm.

Other handy formulas

To obtain the voltage ratio from a given dB, use this formula, where $A=dB$

$$V2/V1=10^{(A20)}$$

To obtain the RMS voltage for any power use:

$$V=\sqrt{\ }(PxR)$$

So for a 100 watts and 50 ohms than the RMS voltage is calculated thus:

$$V=\sqrt{\ }(100x50)=70.71 \text{ volts RMS}$$

What are dB

Decibels state a power ratio, not an amount. They tell how many times more (positive dB) or less (negative dB) but not how much more or less in absolute terms. Decibels are logarithmic, not linear. For example, 20 dB is not twice the power ratio of 10 dB. Use this equation to find decibels: A = 10*log10 (P2/P1) (dB) where P1 is the power being measured, and P1 is the reference to which P2 is being compared. To convert from decibel measure back to power ratio: P2/P1=10^(A/10). Voltage is more easily measured than power, making it generally more convenient to use: A = 20*log10(V2/V1), Where A=voltage ratio. The equation for obtaining voltage ratio from dB is V2/V1 = 10^(A/20).

What are dBm

dBm is an abbreviation for the power ratio in decibels (dB) of the measured power referenced to one milliwatt (mW). It is used in radio and microwave equipment as a convenient measure of absolute power because of its capability to express both very large and very small values in a short form.

Compare dBW, which is referenced to one watt (1000 mW). Since it is referenced to the watt, it is an absolute unit, used when measuring absolute power. By comparison, the decibel (dB) is a dimensionless unit, used for quantifying the ratio between two values, such as signal-to-noise ratio.

Zero dBm equals one milliwatt. A 3 dB increase represents roughly doubling the power, which means that 3 dBm equals roughly 2 mW. For a 3 dB decrease, the power is reduced by about one half, making –3 dBm equal to about 0.5 milliwatt. To express an arbitrary power *P* as *x* dBm, or vice versa, the following equations may be used:

$$X=10log_{10}(100P) \text{ or } x=10log_{10}P+30 \text{ and}$$

$$P=10^{(x/10)}/1000 \text{ or } P=10^{(x-30)}/10$$

Table 1. Relationship of dBm to power and application

dBm level	Power	Application
80 dBm	100 kW	Typical transmission power of FM and TV radio station with about a 31 mile range.
60 dBm	1 kW	Typical combined radiated RF power of microwave oven elements. Approximate maximum RF output power from a ham radio transceiver allowed.
50 dBm	100 W	Typical thermal radiation emitted by a human body. Typical maximum output RF power from a ham radio HF transceiver.
40 dBm	10 W	Typical PLC (Power Line Carrier) Transmit Power.
37 dBm	5 W	Typical maximum output RF power from a handheld ham radio VHF/UHF transceiver.
36 dBm	4 W	Typical maximum output power for a Citizens' band radio station (27 MHz) in many countries.
33 dBm	2 W	Maximum output from a UMTS/3G mobile phone (Power class 1 mobiles). Maximum output from a GSM850/900 mobile phone.
27 dBm	500 mW	Typical cellular phone transmission power. Maximum output from a UMTS/3G mobile phone (Power class 2 mobiles).
20 dBm	100 mW	Bluetooth Class 1 radio. Maximum output power from unlicensed AM transmitter per U.S. Federal Communications Commission (FCC) rules.
–73 dBm	50.12 pW	"S9" signal strength, a strong signal, on the S-meter of a typical ham or shortwave radio receiver.
–127.5 dBm	0.178 fW	Typical received signal power from a GPS satellite
–174 dBm	0.004 aW	Thermal noise floor for 1 Hz bandwidth at room temperature (20 °C)

See Table 1 for typical power levels. It provides an insight into the relationship of dBm to power and application. Note the very wide power range in dBm that can be easily expressed

Making Precision RF Power Measurements

Table 2. It shows calculations for power measurements using an ideal -30dB sampler. Affordable samplers usually have a specification of -30dB +/- 1 db. A 1dB error could have an effect on the measurement accuracy.

Table 2. Sine wave peak and average watts and dBm power, with a -30db sampler

Peak volts at sampler In/Out	Peak volts at sample port (-30db)	Peak Power Watts	Avg. Power Watts	Power in dBm
16	0.50	5	3	37.10
32	1.00	20	10	43.11
47	1.50	44	22	46.45
63	2.00	79	40	48.10
79	2.50	125	62	50.16
95	3.00	181	90	52.56
111	3.50	246	123	53.92
126	4.00	318	159	55.02
142	4.50	403	202	56.06
158	5.00	499	250	56.98
174	5.50	606	303	57.82
190	6.00	722	361	58.59
206	6.50	849	424	59.23
221	7.00	977	488	59.90
237	7.50	1123	562	50.51
253	8.00	1280	640	61.07
269	8.50	1447	723	61.61
285	9.00	1625	812	62.11
300	9.50	1800	900	62.55
316	10.00	1997	998	63.00
332	10.50	2204	1102	63.43
348	11.00	2422	1211	63.84
364	11.50	2650	1325	64.23
379	12.00	2873	1436	64.58
395	12.50	3121	1560	64.94

Consider an ideal sampler with a sample coefficient -30dB. That equates to a voltage gain/loss of 31.62. Then consider a sampler that has a sample coefficient of -31dB. That equates to voltage gain/loss of 35.48. Now consider a sampler with a sample coefficient of -29dB. That equates to a voltage gain/loss of 29.18.

Table 3. Calculates power for each of these examples based only on the voltage gain/loss, results in the following measurement uncertainty:

Table 3 Measurement uncertainty

	-29dB	Ideal -30dB	-31dB
Voltage gain/loss	29.18	31.62	35.48
Calculated power	17.03 watts	20.00 watts	25.18 watts
Approximate Error	17%	0%	21%

For all practical purposes, a 1dB gain or loss in transmitted and or received signals is insignificant and difficult to notice. However, when checking the accuracy of a component in the transmitter chain or using the device as a “ham shack” standard, measurement uncertainty is important. A 1dB error may be significant.

How to improve measurement accuracy

There are three practical ways to improve the accuracy. One expensive way is to compare your power measurement to a laboratory standard. Another, lower cost alternative is to purchase a sampler which was calibrated with NIST traceable equipment. These samplers have the measured transfer coefficient i.e. -30dB stamped on their enclosure. The third, and least expensive alternative, is to calibrate the sampler yourself. You can do this assuming that your oscilloscope has accurately calibrated vertical amplifiers.

See figure 7, a precise method to improve measurement accuracy is to measure the sampler’s RF input voltage (usually with a 10X probe) and compare that measurement to the sampler port output voltage (terminated into 50 ohms). The yellow (top) trace is the sampler port output, and the blue (bottom) trace is sampler RF input. To calculate the voltage gain/loss, using the Pk-Pk voltages will give greater resolution than RMS voltage. That is because Pk-Pk voltages are greater. In our example, we divide 152V/4.52V equals a measured voltage gain/loss of 33.62. From this we determine that the sampler coefficient is -30.53dB, well within the samplers published specification.

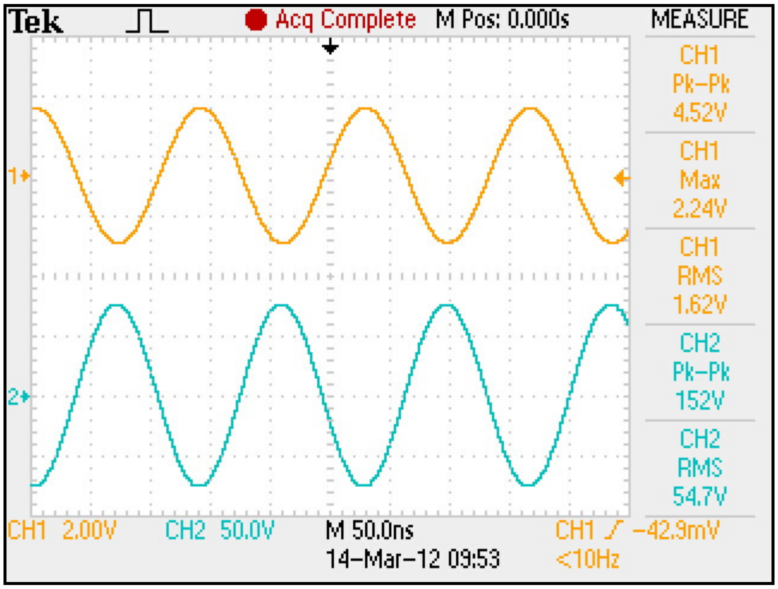

Figure 7 Sampler coefficient

Multiply the sampler port voltage by the sampling gain/loss value and plug it into V_{RMS}. In this case the sampler port voltage Pk-Pk is 4.52V. (The equivalent voltage on the sampler RF input equals 4.52x33.62=152volts). This equals Pk-Pk volts, so we need to calculate RMS:

$$(152 \times .707)/2 = 54.08 \text{ volts RMS}$$

That's pretty close to the measurement (54.7 volts) on our scope in figure 7. The minor difference is attributed to the scope's resolution and specification limits. Finally, to calculate the power we use:

$$P_{avg} = (E_{RMS})^2/R \text{ resulting in}$$

$$(54.08)^2/50 = 58.5 \text{ watts}_{avg.}$$

These types of calculations/measurement will be well within +/- 1% of the scope's specifications. This accuracy is better than that obtained by the +/- 1dB uncertainty.

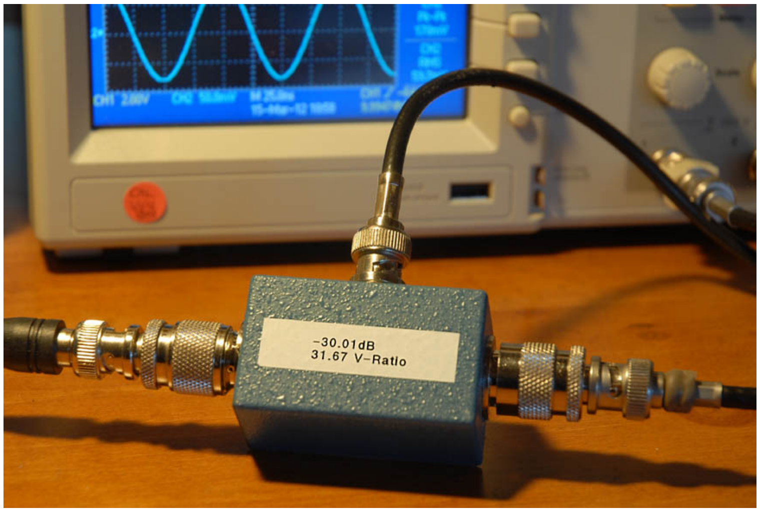

Figure 8, Calibrated Sampler

See figure 8, attach a calibration label on the sampler *"-30.01 dB, & 31.67 V-Ratio"*. Now when you use the "calibrated" sampler, you'll get accurate and consistent results. Table 4, provides a quick way to look-up voltage gain/loss ratios given a sample coefficient from 29dB to 31dB.

Table 4, dB versus voltage gain/loss

Coefficient (dB)	Voltage gain/loss
29.0	28.13
29.1	28.51
29.2	28.84
29.3	29.17
29.4	29.51
29.5	29.85
29.6	30.20
29.7	30.55
29.8	30.90
29.9	31.26
30.0	31.62
30.1	31.99
30.2	32.36
30.3	32.73
30.4	33.11
30.5	33.50
30.6	33.88
30.7	34.28
30.8	34.67
30.9	35.08
31.0	35.48

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